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The measurement of transverse polarization of Λ Hyperons in relativistic heavy ion collisions

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We investigate the transverse polarization of Λ hyperons produced in 11.6 A GeV/c Au-Au collisions at the AGS. E896 provides polarization measurements in two independent detector systems, a Silicon Drift Detector Array at mid-rapidity and a Distributed Drift Chamber at forward rapidity. The data show a dependence of the polarization on the transverse momentum and Feynman-x of the Λ hyperons. The heavy-ion data are consistent with previous measurements in proton-proton and proton-nucleus collisions within statistical errors.

1. Introduction

The spin structure of baryons has been studied extensively during the past three decades. In the past it was assumed that spin effects in hadronic reactions should be of little importance at high energies. At these energies the Λ production mechanism was assumed to proceed via many inelastic channels each naively contributing a different magnitude and sign to the average polarization. It was therefore unexpected that Λ hyperons produced in proton-proton (p-p) and proton-nucleus (p-A) collisions show a large polarization transverse to the production plane. The polarization effect was first observed in 1976 at FNAL in 300 GeV/c proton on Beryllium collisions [1]. Parity conservation in strong production requires that the spin of produced Λ's is aligned normal to the production plane.The data showed that the Λ's in the fragmentation region are preferentially produced with their spin aligned anti-parallel to the production plane. Since then many experiments have systematically measured hyperon polarization covering a large range of of transverse momentum (p_t) and Feynman-x ($x_f = P_\Lambda/P_{beam}$). All experiments show consistently high polarization for high p_t and x_f [1–3].

Many attempts have been made to understand the origin of the polarization of hyperons. Originally, semi-classical parton recombination models assumed that the Λ polarization is exclusively carried by the s-quark, which is recombined with a u-d di-quark in a singlet state in order to form a Λ. The s-quark was either a slow sea-quark [4] or originated via quark-antiquark pair production through a tunneling process in the color field [5]. Based on these recombination models a vanishing polarization of the Λ has been proposed as a possible signature for the formation of a Quark Gluon Plasma (QGP) in relativistic heavy ion collisions [6]. Recent measurements with polarized beams [7] seem to indicate, though, that the semi-classical di-quark, s-quark recombination model is inconsistent with the measured forward-backward asymmetry (A_N) and spin transfer asymmetry (D_{NN}).

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Also, other models like Regge-type models [8] or the more recent quark fragmentation model [9] do not necessarily lead to a change in the hyperon polarization in the case of a QGP.

It seems that the measurement of the polarization of the Λ in relativistic heavy ion collisions would be of interest regardless of the obtained results. Two attempts have been made in the last two decades in heavy ion measurements at the AGS and at CERN [10,11] but in both cases the experiments were not dedicated hyperon measurements and the results were hampered by low statistics and a small kinematic range. Ultimately the measurements were inconclusive and the question of polarization in heavy-ion collisions has never been fully answered.

2. Experiment E896

Experiment E896 at the Alternating Gradient Synchrotron (AGS), at Brookhaven National Laboratory, is a heavy-ion fixed target experiment, utilizing the 11.6 A GeV/c Au beam provided by the AGS in collisions with a 10% interaction length Au target. The experiment was designed to detect short-lived particles, in particular strange and multi-strange baryons through their charged decay products. E896 consists of two main tracking detectors that are operated and analyzed independently from each other. The Au target resides in the gap of a strong super-conducting magnet (B=6.2T). Located at a distance of 8 cm downstream from the target in the strong dipole field is a Silicon tracking detector, the Silicon Drift Detector Array. The SDDA consists of 15 consecutive single plane Silicon drift detectors which cover a rapidity range of $y = 0.8 - 1.8$ and 20^o in radial acceptance. The strong dipole field sweeps out all charged particles and bends the beam sufficiently so that the second tracking device, a Distributed Drift Chamber (DDC), which is located in a second, lower field dipole magnet (B=1.6T), is not traversed by any primary charged particles. The chamber's front face is 132 cm from the target. It consists of 144 planes of 20 micron wires suspended in a flowing helium-ethane (50:50) gas mixture. Its sensitive volume intercepts the neutral-particle line (from the target) and covers an effective range of 2.0-3.2 in rapidity and 2^o in radial acceptance for Λ hyperons, thus observing phase space distinct from the SDDA.

3. Polarization analysis, results and conclusion

The main method to measure Λ polarization is the measurement of the emission angle distribution of the decay proton with respect to the production plane axis. By integrating over the full Λ momentum space the decay proton distribution as a function of emission angle Θ can be expressed as:

$$dN/d\cos\Theta = A(cos\Theta)(1 + \alpha P \cos\Theta), \tag{1}$$

where P is the level of polarization of the Λ, and Θ is the angle between the decay proton and the normal to the production plane in the Λ rest frame. α is an s-p-wave interference term factor which is measured to be 0.642 ± 0.013 [12]. A is the detector response correction factor which has to be determined through simulation of the geometry of the specific measurement device. The polarization in this analysis is defined as the slope of the dN/dcosΘ vs cosΘ distribution between cosΘ = 1 to -1. Based on past results it is apparent that the effect of polarization is very strongly dependent on the kinematic properties of the Λ. The polarization increases with increasing Feynman-x or transverse momentum [1–3]. Polarization in E896 was measured in both tracking detectors, the SDDA and the DDC. The DDC covers the forward rapidities, which means it has x_f-coverage at high x_f (x_f=0.6-1.0), but its transverse momentum coverage is limited to low momentum (p_t=0.05-0.5 GeV/c). In contrast the SDDA is located at mid-rapidity, which translates to a moderate x_f-coverage (x_f=0.0-0.6) and a high p_t-coverage (p_t=0.5-2.0 GeV/c). Thus the two data sets are complementary with very little kinematic overlap. The SDDA data set contains about 15,000 reconstructed Λ's, the DDC data set contains 70,000 reconstructed Λ's. All data were obtained in central Au-Au collisions (top 5% of the geometrical cross section).

Background subtraction and the determination of systematic errors in the analysis will be described in a detailed upcoming paper. Our investigations of the detector geometry and the data background showed that neither effect introduces a bias in the polarization result. The cosΘ distribution for the complete Λ sample in the SDDA integrated over all p_t and x_f is characterized by only a minor slope from which we deduce a polarization of P = -3.0% ± 5.0%, which is consistent with no polarization in the integrated sample. This result is not surprising because the p_t-x_f distribution of the measured Λ's shows that the bulk of the particles in the Silicon detector have low p_t and x_f, which is the kinematic range where no polarization is expected. We thus divide our sample into five x_f bins. The bins were chosen to allow comparison with p-p measurements and to assure comparable statistics in each bin. Based on phase space coverage of the SDDA, Λ's at high x_f also carry a large transverse momentum component. Thus, the cut on x_f is equivalent to a cut in p_t. Fig. 1a shows the polarization results in the SDDA in comparison to the polarization obtained from the background simulation. Fig. 1b shows the DDC results as a function of x_f. The DDC x_f-range exceeds x_f=1 due to Fermi motion of the particles and, to a lesser extent, due to detector resolution. The tables summarize the results from all measurements in the SDDA and the DDC. Both detectors measure a negative polarization signal at high x_f and high p_t. The data indicate a steady increase in polarization with p_t and x_f. In particular the high p_t, high x_f bin ($p_t \geq 1.5$ GeV/c and $x_f \geq 0.5$) in the SDDA exhibits a polarization of P = -25.7% ± 7.5%, while it is found to be -23.0% ± 11% in the highest bin of the DDC. These measurements are the first to confirm Λ polarization in Λ's produced in a heavy ion collision.

Our results show that in the heaviest collision systems the produced Λ's are still polarized at freeze-out which means the spin direction is only little affected by the rescattering phase after hadronization. The fact that the polarization is formed in these heavy-ion collisions and is at the level of polarization measured in p-p reactions indicates that the production mechanism of Λ's, even in this highly collective system, is similar to the production mechanism in basic p-p reactions. Establishing the occurance of polarization in a heavy ion system will allow even stronger conclusions from a possible disappearance of polarization in heavy-ion collisions at higher energies. The STAR detector will be capable of repeating these measurements at RHIC energies.

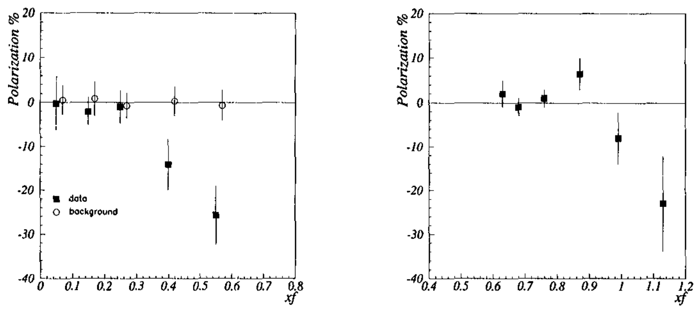

Figure 1. a.) Λ polarization measured in the SDDA compared to the polarization obtained in the background sample, b.) Λ polarization measured in the DDC

SDDA x_f, $<p_t>$ **in GeV/c**	**Polarization**
x_f=0.05, $<p_t>$=0.57	-0.3±6.0%
x_f=0.15, $<p_t>$=0.79	-2.1±3.2%
x_f=0.25, $<p_t>$=1.23	-1.0±3.8%
x_f=0.4, $<p_t>$=1.61	-14.1±6.0%
x_f=0.55, $<p_t>$=1.98	-25.7±7.5%

DDC x_f,$<p_t>$ **in GeV/c**	**Polarization**
x_f=0.63, $<p_t>$=0.05	2.0±3.0%
x_f=0.68, $<p_t>$=0.15	-1.0±2.0%
x_f=0.76, $<p_t>$=0.25	1.0±2.0%
x_f=0.87, $<p_t>$=0.35	6.5±3.5%
x_f=0.99, $<p_t>$=0.45	-8.0±6.0%
x_f=1.13, $<p_t>$=0.55	-23.0±11.0%

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